THERMOSCIENCES DIVISION

Final Report

on

GRADUATE RESEARCH TRAINING IN ADVANCED DIAGNOSTICS TECHNIQUES (AASERT)

Grant AFOSR F49620-97-1-0371

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period

June 1, 1997 to November 30, 2000

Submitted by

R. K. Hanson, Principal Investigator

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Tunable diode laser absorption probes have been developed for characterization of short-duration hypersonic flows produced in shock tunnels and expansion tubes. A new single-wavelength probe was tested in a large reflected shock tunnel at Calspan and in an expansion tube at Stanford. The demonstrated success of this sensor in characterizing the time evolution of freestream velocity should improve the utility of aerodynamic test data obtained in high-enthalpy hypersonic tunnels and should also provide a means of monitoring the effects of facility modifications aimed at increasing test time and flow steadiness. Good agreement was found over the full range of velocities observed (up to 5.0 km/sec) when the water vapor and potassium probes were employed simultaneously.

Infrared PLIF imaging techniques have been developed for imaging of CO and CO2 in flames. These diagnostics employ tunable optical parametric oscillators or high-pulse-energy gas lasers in the infrared to excite vibrational transitions in molecules, and use infrared cameras to image vibrational (infrared) fluorescence. These techniques have been demonstrated in flows ranging from room-temperature mixing to laminar diffusion flames.

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Abstract

Tunable diode laser absorption probes have been developed for characterization of short-duration hypersonic flows produced in shock tunnels and expansion tubes. A new single-wavelength probe was tested in a large reflected shock tunnel at Calspan and in an expansion tube at Stanford. The demonstrated success of this sensor in characterizing the time evolution of freestream velocity should improve the utility of aerodynamic test data obtained in high-enthalpy hypersonic tunnels and should also provide a means of monitoring the effects of facility modifications aimed at increasing test time and flow steadiness. Good agreement was found over the full range of velocities observed (up to 5.0 km/sec) when the water vapor and potassium probes were employed simultaneously.

Infrared PLIF imaging techniques have been developed for imaging of CO and CO_2 in flames. These diagnostics employ tunable optical parametric oscillators or high-pulse-energy gas lasers in the infrared to excite vibrational transitions in molecules, and use infrared cameras to image vibrational (infrared) fluorescence. These techniques have been demonstrated in flows ranging from room-temperature mixing to laminar diffusion flames.

1. Objectives

This program supports one doctoral graduate student engaged in research on advanced laser diagnostic methods for combustion gases. The emphasis at the beginning of the grant was on wavelength-multiplexed laser absorption using rapid-scanning near-infrared diode laser sources, and (upon graduation of that student) has been infrared PLIF imaging of CO and CO_2. The objective of the research is to establish new classes of nonintrusive instrumentation for monitoring combustion flows related to air-breathing propulsion.

2. Status of Effort

Funding for this AASERT program began on June 1, 1997 and supports one graduate student. During the period covered by the present report, the research of the two students supported by this grant has yielded numerous technical presentations and five archival publications.

3. Accomplishment/New Findings

The diode laser absorption sensors developed in this program provide the first capability for nonintrusive measurements of velocity, rotational and translational temperature, and pressure at hypersonic conditions. The infrared PLIF imaging techniques provide the first capability for PLIF imaging of CO_2 in flames.

4. Technical discussion of Tunable Diode Laser Probe

Recent experiments have demonstrated the capability and robustness of tunable diode laser absorption spectroscopy (TDLAS) techniques to measure temperature and velocity in high-enthalpy flowfields. An added benefit of this approach is the ability to diagnose the presence of

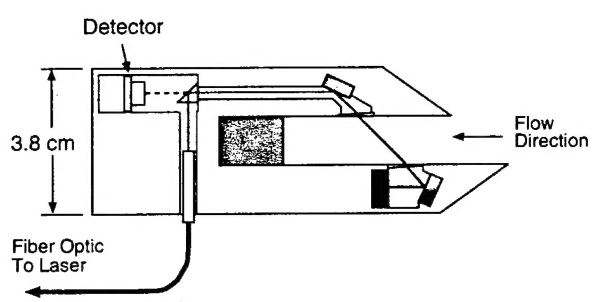

Fig. 1. A schematic of a new TDL probe for measurements of potassium in hypervelocity flowfields. This improved version uses a single counter propagating beam to measure blue and red shifted absorption features to measure velocity.

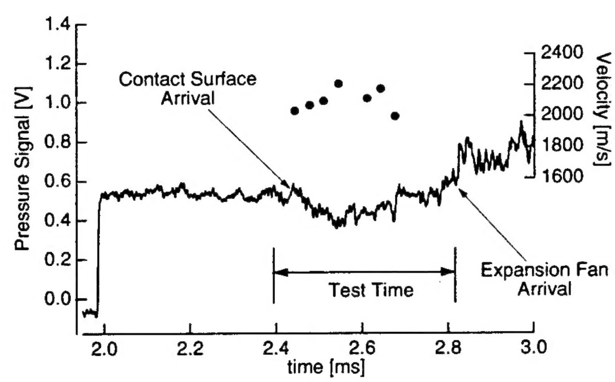

Fig. 2. Data traces from a 4.0 MJ/kg test performed in Stanford's Expansion Tube Facility. The solid black trace is a static pressure signal. A change in its signature indicates the arrival of the contact surface and coincides with the arrival of potassium. An average velocity of 2200 m/s was obtained.

minor or contaminant species. We have developed two separate TDLAS systems, one based on water vapor and a second based on atomic potassium. Water vapor is a critical contaminant when operating a hypersonic shock tunnel with a hydrogen driver, but of course is present as a product of combustion in scramjet testing. On the other hand, potassium has been discovered to exist naturally in minute quantities in Stanford's expansion-tube facility and in Calspan's 96" hypersonic shock tunnel (HST). This suggests the opportunity to capitalize on such tracer species without a perturbation to flowfield composition.

In Fig. 1, a schematic of a hardened potassium probe is shown. This probe contains the electro-optics required to pitch and catch laser beams through an undisturbed flow. Light is fed to the probe via a fiber-coupled diode laser system located remotely from the test facility.

Recently the TDL probe was used to examine the velocity time history in the Stanford expansion tube; a sample set of results is shown in Fig. 2. The potassium probe was situated at the exit plane of the expansion tube section and exposed to the following nominal free stream conditions: V = 2400 m/s, T = 1200 K, and P = 145 torr. Fluctuations in the measured velocities are attributed both to actual variations in velocity and to temporal fluctuations in the potassium levels. We attributed a portion of the difference in measured and calculated velocity to the effects of enhanced absorption in the slow-moving, hot boundary layers adjacent to the probe. Current efforts are directed towards improved seeding strategies and reducing the signal contribution from boundary layers.

5. Technical discussion of IR PLIF Imaging

New planar laser-induced fluorescence diagnostics have been developed for species which do not have accessible single-photon electronic spectra. These species include many critical combustion products and fuels (CO, CO_2, H_2O, CH_4, C_2H_6, C_3H_8). Though planar laser-induced fluorescence (PLIF) diagnostics have played a key role in design and analysis of combustion systems, they have not in the past been able to provide images of these critical species. However, new technological advances in infrared laser sources and infrared camera systems have revolutionized the possibilities for infrared imaging. We have exploited these new technological developments and novel excitation and detection strategies to perform infrared planar-laser induced imaging of CO and CO_2.

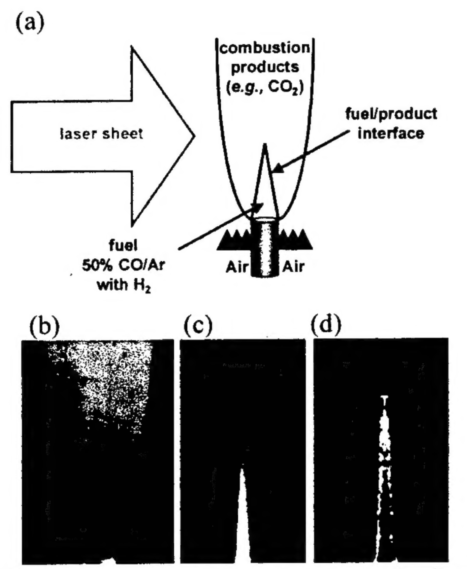

Fig. 3. (a): Schematic of CO-fueled laminar diffusion flame. (b): IR PLIF image of CO_2 using 10.6 μm laser excitation. (c): IR PLIF image of CO using 2.3 μm excitation. (d): IR PLIF image of CO/CO_2 region overlap using combined 2.3 μm/VET excitation.

Accomplishments include: demonstration of the first infrared (IR) PLIF diagnostics for CO and CO_2, the first detailed analysis of excitation schemes for these species, the first results using saturated laser excitation, and the first techniques which use combined laser/VET pumping

schemes. These diagnostic developments, examples of which are shown in Figure 3, take advantage of recent advances both in IR laser sources (based on optical parametric oscillators) and IR cameras (based on indium antimonide focal plane arrays). We expect that these IR PLIF diagnostics will eventually be used for a variety of purposes, e.g., to identify toxic formation/removal zones (CO), localize regions of heat release (CO_2, H_2O), and evaluate fuel mixing processes (CO, CH_4), all of which expand the combustion community's ability to design and analyze air-breathing propulsion systems.

6. Personnel Supported

The graduate student supported over the first two years of this grant was Mr. Shawn Wehe; upon his graduation, Mr. Brian Kirby was supported during the final year.

7. Publications and Selected Presentations

S.D. Wehe, D.S. Baer, R.K. Hanson and K.M. Chadwick, "Gas Temperature and Velocity Measurements in Hypervelocity Flows Improved Diode-Laser Absorption Sensors," 22nd Int'l. Shock Tube and Shock Wave Symp., London, UK, June, 1999.

Kirby, B.J. and Hanson, R.K. "Planar laser-induced fluorescence imaging of carbon monoxide using vibrational (infrared) transitions," *Applied Physics B* Vol. 69 No. 5/6,1999.

Kirby, B.J. and Hanson, R.K. "Imaging of CO and CO_2 using infrared planar laser-induced fluorescence," *Proceedings of the Combustion Institute*,Vol.28, 2000, in press.

Kirby, B.J. and Hanson, R.K. "Design and analysis of excitation schemes for IR PLIF imaging of CO and CO_2," Submitted to *Applied Optics*, October 2000.

Kirby, B.J. and Hanson, R.K. "CO_2 imaging in flames using saturated planar laser-induced vibrational fluorescence," Submitted to *Applied Optics*, October 2000.

S.D. Wehe, D.S. Baer and R.K. Hanson, "Diode-Laser Sensor for Velocity Measurements in Hypervelocity Flows," *AIAA J.*, **37** (8), 1999.

D.S. Baer, S. Sanders, S. Wehe and R.K. Hanson, "Diode-Laser Absorption Sensors for Real-time *in situ* Measurements," invited presentation at OSA Annual Meeting, Santa Clara, CA, October, 1999.

8. Interactions/Transitions

Discussions are underway with research scientists at GASL and NASA Langley Research Center regarding possibilities for transferring our TDL probe technology for use in GASL facilities. We have also interacted with Boeing regarding implementing IR PLIF techniques for exhaust reinjection studies on the Joint Strike Fighter.

9. New Discoveries

This probe concept was developed initially at Stanford under support of a regular AFOSR grant. The new K-atom probe can be attributed entirely to the current AASERT grant. IR PLIF imaging techniques have been developed under support of a regular AFOSR grant; the use of TEA CO_2 lasers for saturated excitation and PLIF imaging of CO_2 can be attributed entirely to the current AASERT grant.

10. Honors/Awards

Fellow of the Optical Society of America, 1990
R. K. Hanson
Optical Society of America

Technical Excellence in Imaging, 1995
R. K. Hanson and J. L. Palmer
Visualization Society of Japan

Aerodynamic Measurement Technology Award (First Recipient), 1996
R. K. Hanson
American Institute of Aeronautics and Astronautics (AIAA)

Fellow of the American Institute of Aeronautics and Astronautics, 1997
R. K. Hanson
American Institute of Aerodynamics and Astronautics (AIAA)

AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT) REPORTING FORM

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT Program. By accepting this Grant which bestows the AASERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information should be provided to the Government's technical point of contract by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R&T and Grant numbers found on Page 1 of Grant)

   a. Stanford University
      University Name

   b. F49620-97-1-0371
      Grant Number

   c.
      R&T Number

   d. Ronald K. Hanson
      P.I. Name

   e. From: June 1 1997 To: November 30 ~~2000~~
      AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referrred to hereafter as "Parent Agreement".

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

   a. Funding: $ 312,000

   b. Number FTEGS: 5

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month period.

   a. Funding: $ 333,260

   b. Number FTEGS: 5

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

   a. Funding: $ 49,770

   b. Number FTEGS: 1

   c. Number UGS: 0

VERIFICATION STATEMENT: I hereby verify that all students supported by the AASERT award are U.S. Citizens.

R. Hanson
Principal Investigator

Date: October 14, 2000

Stanford University